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Pilot-in-the-Loop CFD Method Development

Progress Report (CDRL A001)

Progress Report for Period: July 1, 2014 to July 31, 2014

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Section I: Project Summary

1. Overview of Project

This project is performed under the Office of Naval Research program on Basic and Applied Research in Sea-Based Aviation (ONR BAA12-SN-0028). This project addresses the Sea Based Aviation (SBA) virtual dynamic interface (VDI) research topic area "Fast, high-fidelity physics-based simulation of coupled aerodynamics of moving ship and maneuvering rotorcraft". The work is a collaborative effort between Penn State, NAVAIR, and Combustion Research and Flow Technology (CRAFT Tech). This document presents progress at Penn State University.

All software supporting piloted simulations must run at real time speeds or faster. This requirement drives the number of equations that can be solved and in turn the fidelity of supporting physics based models. For real-time aircraft simulations, all aerodynamic related information for both the aircraft and the environment are incorporated into the simulation by way of lookup tables. This approach decouples the aerodynamics of the aircraft from the rest of its external environment. For example, ship airwake are calculated using CFD solutions without the presence of the helicopter main rotor. The gusts from the turbulent ship airwake are then re-played into the aircraft aerodynamic model via look-up tables. For up and away simulations, this approach works well. However, when an aircraft is flying very close to another body (i.e. a ship superstructure), aerodynamic coupling can exist. The main rotor of the helicopter distorts the flow around the ship possibly resulting significant differences in the disturbance on the helicopter. In such cases it is necessary to perform simultaneous calculations of both the Navier-Stokes equations and the aircraft equations of motion in order to achieve a high level of fidelity. This project will explore novel numerical modeling and computer hardware approaches with the goal of real time, fully coupled CFD for virtual dynamic interface modeling & simulation.

Penn State is supporting the project through integration of their GENHEL-PSU simulation model of a utility helicopter with CRAFT Tech's flow solvers. Penn State will provide their piloted simulation facility (the VLRCOE rotorcraft simulator) for preliminary demonstrations of pilot-in-the-loop simulations. Finally, Penn State will provide support for a final demonstration of the methods on the NAVAIR Manned Flight Simulator.

2. Activities this period

During the period of this report, the one-way integration of SFS2 (Simplified Frigate Shape 2) ship model airwake (obtained by using CRAFT Tech's flow solvers) and GENHEL-PSU helicopter simulation code has been completed. The GENHEL-PSU simulation was performed with a non-linear dynamic inversion control law using the new SFS2 airwake data. Results have been validated with experimental data.

The unsteady flow over SFS2 ship model had been obtained during the period of June monthly report. Using these results, a small subdomain (435ft x 150ft x 85ft) was extracted from the full scale domain. This subdomain is located right behind the superstructure of the ship and lies between 365 - 800 ft. in x-axis, -75 - 75 ft. in y-axis and 15 - 100 ft. in z-axis with a uniform node spacing of 5ft in all directions. The airwake axes are: x – aft, y – starboard, z – up.

The actual grid used for the CFD analysis was generated using unstructured type grid. However, the current version of GENHEL-PSU Airwake code supports only structured type grids. So the CFD results had to be converted into structured grid type. In order to do that, MATLAB has been used to interpolate the scattered data onto a uniform structured grid. Linear interpolation method was used for data conversion. MATLAB uses Delaunay triangulation method to draw a triangle that encloses the query point and once the point is found, it computes the weighed sum of values of the three vertices of the enclosing triangle.[1] Figure 1 shows the sub-

domain, extracted from full scale domain. The grid on the left is the actual grid structure used in CFD analysis. The grid on the right is the structured grid which the scattered data is interpolated to.

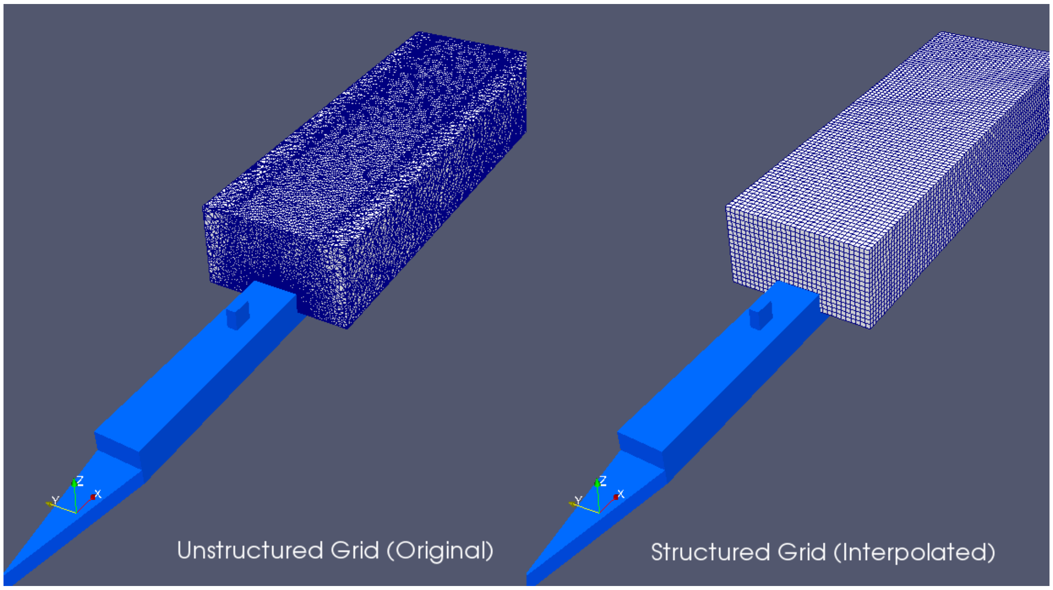

Figure 1 –The subtracted domain used for GENHEL-PSU – SFS2 Ship Model Airwake integeration.

Interpolated results have been imported to Paraview, an open-source, multi-platform data analysis and visualization application, to validate the results visually. Figure 2 shows the contour plots of velocity component in x direction located at y=0.0 for the unstructured (actual) and the structured (interpolated) grids. It can be seen that the interpolated results are in a good correlation with the actual results. The structured (interpolated) grid has a lower mesh resolution compared to the unstructured grid. This causes some data loss on some regions of the domain especially the ones close to the ship surface. However, the resolution is still quite high enough for a helicopter simulation.

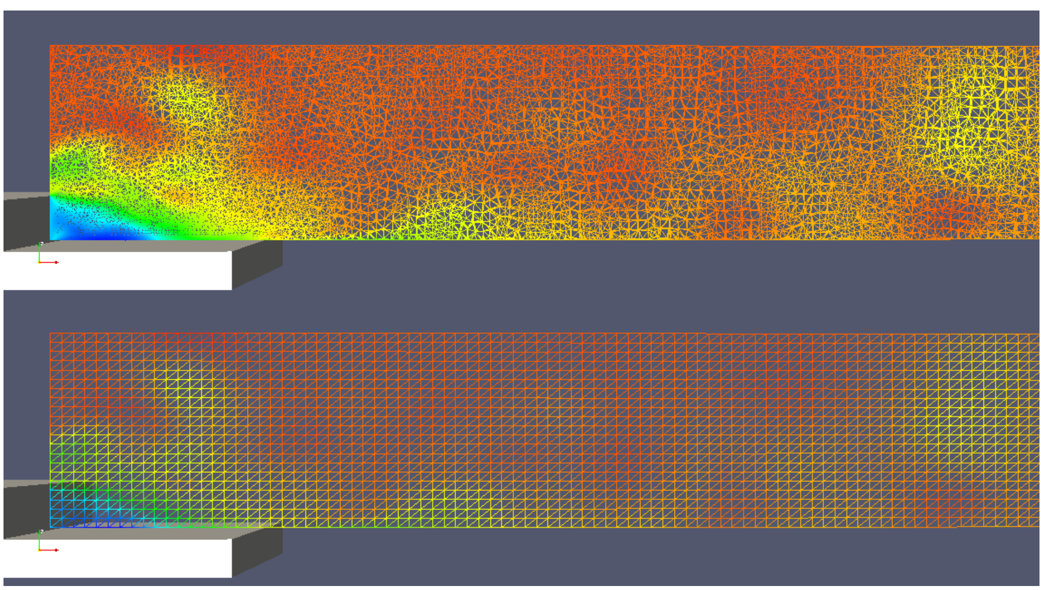

Figure 2 –U-velocity contour plots on a slice located at y=0.0, unstructured & structured grid, t = 10.0th sec.

Figure 3 shows the comparison of time-averaged streamwise non-dimensional velocity distributions over flight deck over four different planes(locate at 0%, 25%, 50% and 75% of the deck) on the rear ship-deck between the unstructured (left) and structured (right) grid computation results. The agreement is pretty good. On some regions, there are some small differences between actual (unstructured) and interpolated (structured) data. However, these regions are small enough and the errors are acceptable.

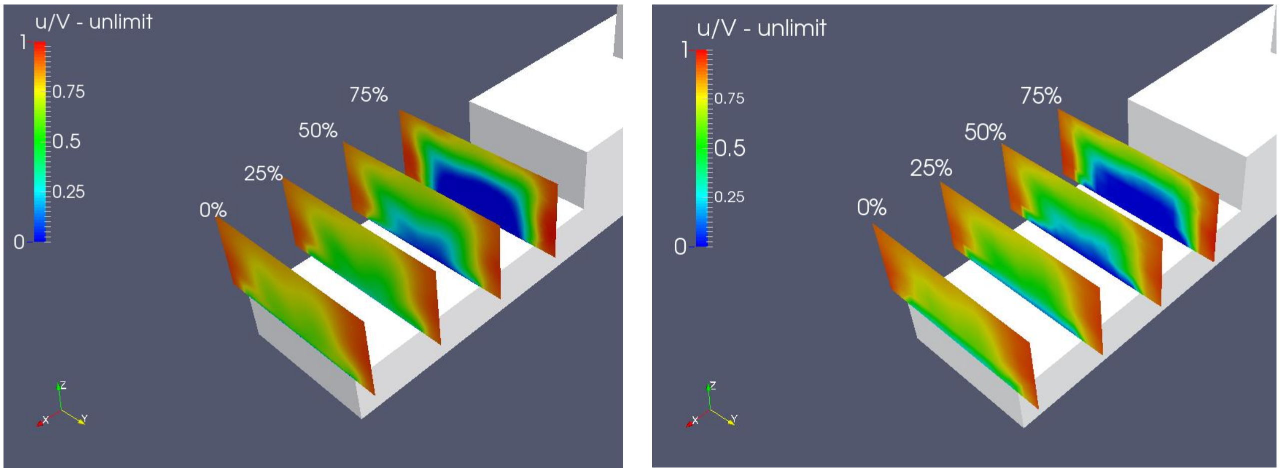

Figure 3 – a) Time-averaged streamwise velocity distributions over flight deck, CFD – Unstructured Grid(actual), b) Time-averaged stream wise velocity distributions over flight deck, CFD – Structured Grid (Interpolated)

Figure 4-5 show the comparison of streamwise and vertical velocity distributions over three different planes on the rear ship-deck for the actual and the interpolated data, respectively. The plots also show the measured data obtained from [2] at 20 ft. above the deck. Compared to the results that we obtained during the period of June progress report (left), the agreement is still good for both the streamwise and the vertical velocity component obtained from interpolated data. The differences between the full CFD and the interpolated CFD data are the result of low grid resolution on interpolated data and the errors of linear interpolation method. However, results are still acceptable.

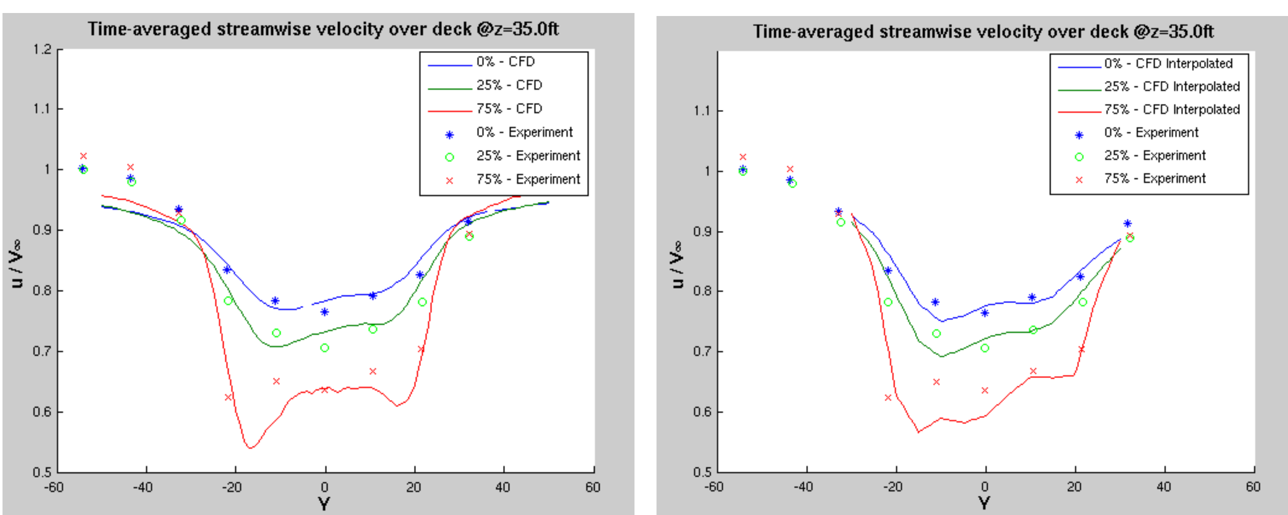

Figure 4 – Time-averaged streamwise velocities over deck at different planes, actual calculated data(left), interpolated data(right)

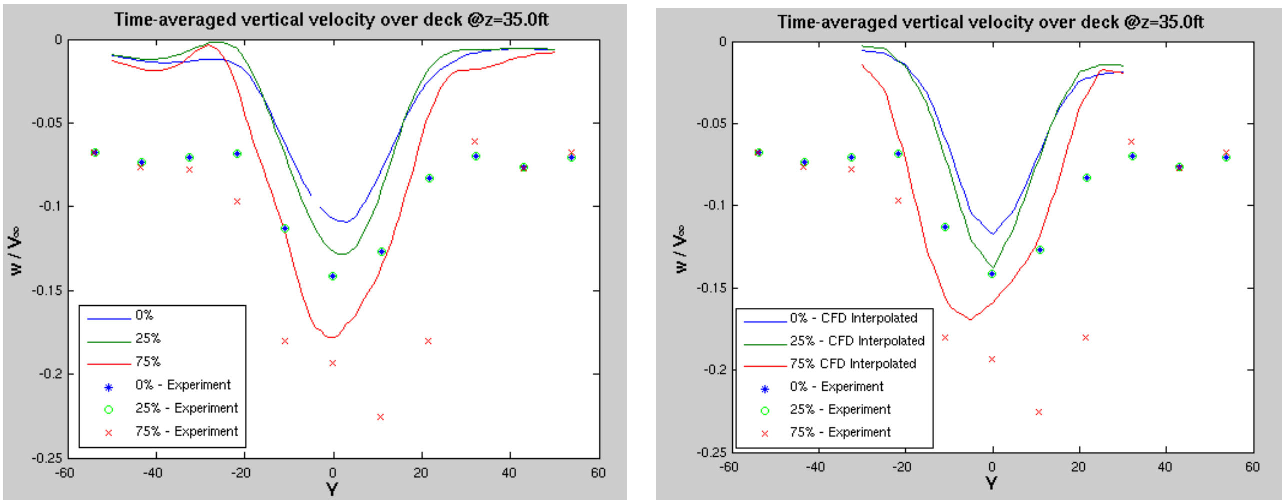

Figure 5 – Time-averaged vertical velocities over deck at different planes, actual CFD data(left), interpolated CFD data(right)

The one way coupled SFS2 airwake data has been successfully integrated to the GENHEL-PSU. In initial tests, GENHEL-PSU simulation was performed with a non-linear dynamic inversion control law developed in recent work at PSU [3]. The time history results of X-Y-Alt positions (ft), attitude angles (deg) and gust velocity components (ft/sec) are shown in Figure 6-8 for the simulated helicopter hovering over the deck of SFS2 ship in 25 knot, 0 degree wind-over-deck conditions. As seen, the controller holds the position over the deck (within 5 ft of the original position) and the airwake has a time-varying disturbance on the helicopter (as seen by the larger attitude and position fluctuations with the airwake). Figure 6 shows the airwake disturbance on the fuselage as recorded in the simulation model. Similar disturbances also act on the rotor, tail rotor, and empennage causing forces and moments that disturb the aircraft. The controller reacts to these disturbances to hold position. Figures 7 and 8 show the response in position and attitude of the closed loop aircraft undergoing disturbance. The results are reasonable and show similar response as one-way coupled simulation with an LHA airwake developed in previous studies at PSU.

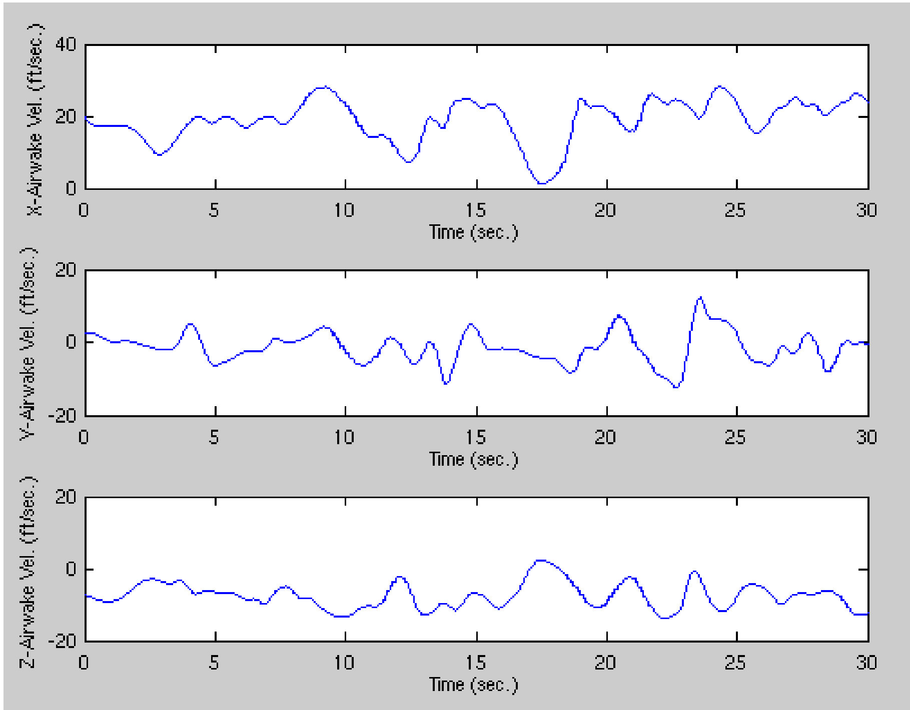

Figure 6 – Change in gust velocity components applied to aircraft during simulation

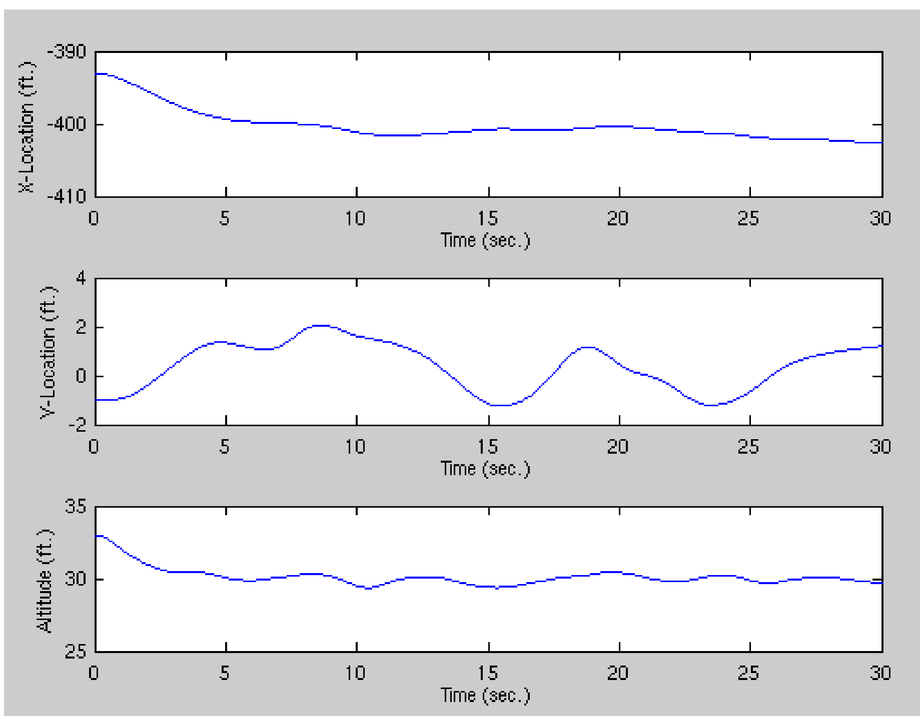

Figure 7 – Variation in positions of the simulated helicopter with TRC (Transitional Rate Command) Controller

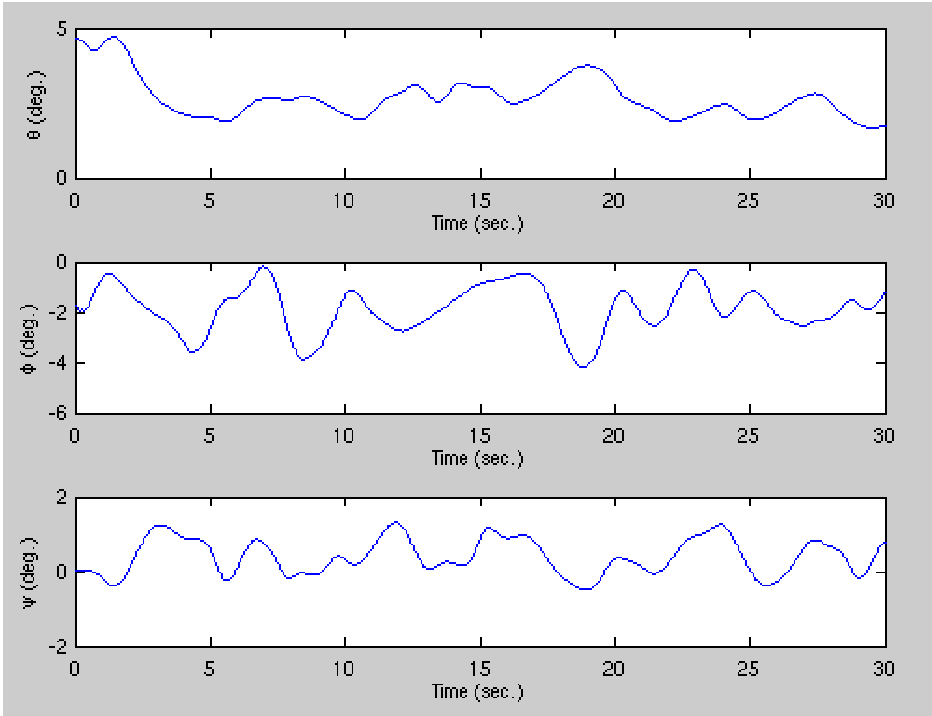

Figure 8 – Attitude response of the simulated helicopter with TRC (Transitional Rate Command) Controller

The next step in the project is to set up fully coupled simulation with GENHEL-PSU and CRUNCH. PSU is currently coordinating with CRAFT Tech on acquiring the appropriate version of CRUNCH to incorporate the coupling effects.

3. Significance of Results

The results show the successful one-way integration of the SFS2 airwake (obtained by using CRAFT Tech's flow solver) and GENHEL-PSU simulation code. These results will provide a baseline with which to compare the fully coupled solutions in next stages of this study.

4. Plans and upcoming events for next reporting period

- Continue development of fully-coupled simulations: In fully coupled solutions, blade position and aero loads are transmitted to the CFD code, the CFD code then calculates a velocity field (including the induced velocities from the aircraft airloads) and sends these velocity values back to the helicopter simulation model. The subsequent airloads and dynamics of the helicopter are then affected by the evolving external flow field. In this sense, the CFD solutions serve the purpose of not only the ship airwake effects but of the induced flow field generated by the helicopter main rotor (and possibly other components of the aircraft). Induced flow in the rotor is usually modeled by a lower order model in flight simulations (e.g. finite state inflow), but these modules will be replaced by CFD in the coupled solutions.
- Initial coupled solutions will not involve ship flow fields. Coupled simulations will be performed with the helicopter hovering in an open domain. The helicopter will be trimmed and perform an extended hover using the controller. The performance and trim of the helicopter will be compared to those predicted by the simulation model without coupled CFD. We expect to begin development of these solutions in August, with results expected later this summer.

5. References

1. Interpolating Scattered Data – MATLAB & Simulink, Website, http://www.mathworks.com/help/matlab/math/interpolating-scattered-data.html, Aug 20, 2014.

2. Zhang F., and Xu. H., “Numerical Simulation of Unsteady Flow over SFS 2 Ship Model,” AIAA-2009-0081, 47th Aerospace Sciences Meeting, Orlando, FL, Jan. 5-8, 2009.

3. Soneson, G.L., and Horn, J.F., “Simulation Testing of Advanced Response Types for Ship-Based Rotorcraft,” Proceedings of the American Helicopter Society 70th Annual Forum, Montreal, Canada, May 2014

6. Transitions/Impact

No major transition activities during the reporting period.

7. Collaborations

Penn State has collaborated with CRAFT Tech and conducted regular discussion with them.

8. Personnel supported

Principal investigator: Joseph F. Horn

Graduate Students: Ilker Oruc, PhD Student

9. Publications

No publications to date.

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